Mission Profile-Oriented Control for Reliability and Lifetime of Photovoltaic Inverters

Sangwongwanich, Ariya; Yang, Yongheng; Séra, Dezso; Blaabjerg, Frede

Published in:
I E E E Transactions on Industry Applications

DOI (link to publication from Publisher):
10.1109/TIA.2019.2947227

Publication date:
2020

Document Version
Accepted author manuscript, peer reviewed version

Mission Profile-Oriented Control for Reliability and Lifetime of Photovoltaic Inverters

Ariya Sangwongwanich, *Member, IEEE,* Yongheng Yang, *Senior Member, IEEE,* Dezso Sera, *Senior Member, IEEE,* and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—With the aim to increase the competitiveness of solar energy, the high reliability of Photovoltaic (PV) inverters is demanded. In PV applications, the inverter reliability and lifetime are strongly affected by the operating condition that is referred to as the mission profile (i.e., solar irradiance and ambient temperature). Since the mission profile of PV systems is location-dependent, the inverter reliability performance and lifetime can vary considerably in practice. That is, from the reliability perspective, PV inverters with the same design metrics (e.g., component selection) may become over- or under-designed under different mission profiles. This will increase the overall system cost, e.g., initial cost for over-designed cases and maintenance cost for under-designed cases, which should be avoided. This paper thus explores the possibility to adapt the control strategies of PV inverters to the corresponding mission profiles. With this, similar reliability targets (e.g., component lifetime) can be achieved even under different mission profiles. Case studies have been carried out on PV systems installed in Denmark and Arizona, where the lifetime and the energy yield are evaluated. The results reveal that the inverter reliability can be improved by selecting a proper control strategy according to the mission profile.**

***Index Terms*—PV inverters, lifetime, reliability, mission profile, control, power device, capacitor.**

I. Introduction

There is a strong demand to further reduce the cost of PV energy, in order to increase its competitiveness and enable more harvesting of the renewable energy [1]. For instance, the U.S. Department of Energy has set a target to reduce the cost of PV energy from 0.18 USD/kWh (in 2016) to 0.05 USD/kWh by 2030 (for residential PV systems in the USA) [2]. The similar cost reduction tendency is also expected in other countries globally [3]–[5]. In order to achieve this target, PV systems should be improved in several aspects. Among those, enhancing the reliability and lifetime of PV inverters has high potential for a significant cost reduction [5]. The field experience has shown that the PV inverter failure contributes to a large portion of the unexpected operating and maintenance cost [6]–[9]. This may negatively affect the overall cost of energy in addition to the energy production loss during the inverter downtime periods. Thus, avoiding PV inverter replacements during the entire lifespan of PV power plants (e.g., 20 years) is one of the keys to the cost reduction of PV systems [10].

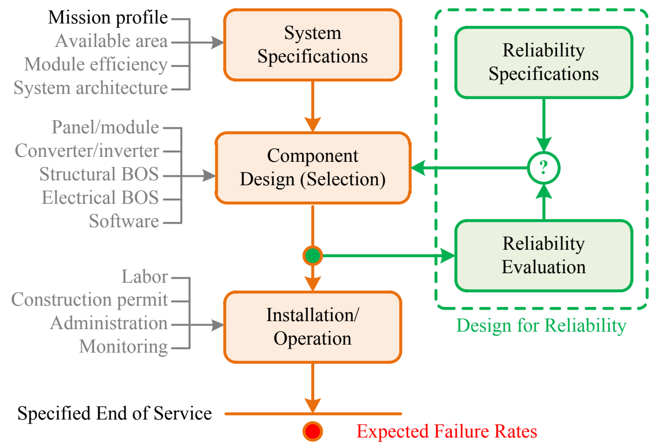


Fig. 1. Diagram of the Design for Reliability (DfR) approach applied to the design of power electronics in PV systems (BOS: Balance of System) [14].

Accordingly, the reliability engineering approach has recently been more involved in the design phase of PV inverters (in general, power electronic systems) [11]–[15]. This is normally referred to as a Design for Reliability (DfR) approach, as it is illustrated in Fig. 1. Following the DfR approach, the reliability specification (e.g., the lifetime target) is defined and it should be fulfilled during the design phase. In this respect, the lifetime prediction tool plays an important role in assessing the reliability of the designed inverter under given operating conditions (e.g., the mission profile of the installation site).

In the prior-art research, it is suggested that the reliability and lifetime of power electronic systems (e.g., PV inverters) are strongly affected by the operating conditions [16]–[22], referred to as mission profiles. Thus, the mission profile is usually required as an input of the DfR process as shown in Fig. 1. For PV applications, the solar irradiance and the ambient temperature are normally considered as the components of a mission profile, as they determine the PV power production (i.e., the PV inverter loading). Since the solar irradiance and ambient temperature are location-dependent (due to the climate condition of the installation site), the mission profile can vary significantly, and thus the reliability

Manuscript received February 12, 2019; revised July 12, 2019 and August 30, 2019; accepted October 5, 2019. This work was supported in part by Innovation Fund Denmark through the Advanced Power Electronic Technology and Tools (APETT) project and in part by the Reliable Power Electronic-Based Power System (REPEPS) project at the Department of Energy Technology, Aalborg University as a part of the Villum Investigator Program funded by the Villum Foundation.

A. Sangwongwanich, Y. Yang, D. Sera, and F. Blaabjerg are with the Department of Energy Technology, Aalborg University, DK-9220 Aalborg, Denmark (e-mail: ars@et.aau.dk; yoy@et.aau.dk; des@et.aau.dk; fbl@et.aau.dk).

This is the reference copy of the accepted version. When it is published, color versions of one or more of the figures in this paper will be available online at http://ieeexplore.ieee.org.

of PV inverters [19]–[22]. From the design perspective, this is a challenge for the DfR approach, where the concept of "one design fits all" is difficult to be achieved. For instance, if the PV inverter is designed to achieve the lifetime of 20 years under cold climate conditions (e.g., low average solar irradiance level), there is a high risk that the same inverter design (e.g., component selection and cooling system design) will not fulfill the reliability target when it is installed in a hot climate region (e.g., high average solar irradiance level). On the other hand, the PV inverter designed with respect to the hot climate condition with strong average solar irradiance and high ambient temperature will be considered as an over-designed case for other installation sites with cold climate conditions. This is not preferable in the DfR concept, as it will increase the overall system cost, e.g., initial cost for over-designed cases and maintenance cost for under-designed cases. Moreover, applying different inverter designs according to installation sites is impractical with respect to the cost.

Actually, the inverter control strategies can affect the reliability and lifetime performances in addition to the mission profile. However, with the conventional Maximum Power Point Tracking (MPPT) operation, the loading of the PV inverters will be dictated by the available power production of the PV arrays. In that case, the PV power variations (reflecting mission profile characteristics) can induce thermal fluctuations on the inverters. In contrast, a Power Limiting Control (PLC) scheme, which limits the maximum feed-in power to a certain level, can smooth the temperature variations and lower the thermal loading to some extent [23]–[25]. This control strategy has initially been introduced to mitigate the overloading issue due to peak power generation of the PV systems [26], [27]. However, this operation also contributes to improved lifetime, which can also be seen in smart de-rating control strategies [28]–[30]. This opens a direction to enhance the reliability and lifetime of PV inverters through a proper control, where the mission profiles are considered in the control design. The concept of adapting the control strategy according to the mission profile for the PV inverter reliability enhancement has been briefly discussed in [31].

In this paper, which is an extension of the authors' previous work in [31], a comprehensive analysis of the PLC being applied to the mission profile-oriented control for reliability and lifetime of PV inverters is provided. This includes the detailed implementation of the control algorithm as well as the impact of the proposed control strategy on the thermal stress and eventually the reliability of the components in PV inverters. The proposed strategy is applied to 6-kW single-phase PV inverters, as described in Section II. In Section III, the lifetime evaluation of PV inverters is presented, where two mission profiles in Denmark and Arizona are used. The results in Section IV demonstrate that the same reliability target (e.g., the lifetime target of 20 years) can be achieved under both mission profiles with the PLC strategy, where the design guidelines are provided in Section V. Finally, concluding remarks are provided in Section VI.

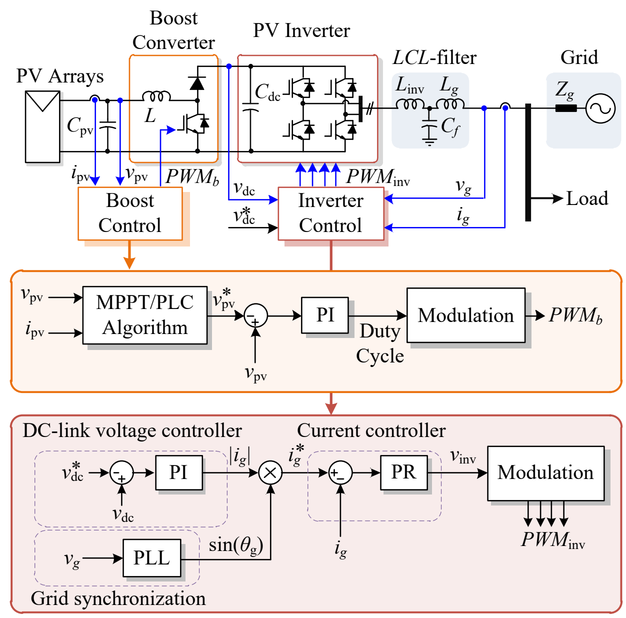


Fig. 2. System configuration and control structure of a two-stage single-phase grid-connected PV system (MPPT: Maximum Power Point Tracking, PLC: Power Limiting Control, PI: Proportional Integral, PR: Proportional Resonant, PLL: Phase-Locked Loop, PWM: Pulse Width Modulation).

TABLE I
PARAMETERS OF THE TWO-STAGE SINGLE-PHASE PV SYSTEM (FIG. 2).

PV inverter rated power	6 kW
Boost converter inductor	L = 1.8 mH
DC-link total capacitance	C_{dc} = 1100 μF
LCL-filter	L_{inv} = 4.8 mH, L_g = 2 mH, C_f = 4.3 μF
Switching frequencies	Boost converter: f_b = 16 kHz, PV inverter: f_{inv} = 8 kHz
DC-link reference voltage	v_{dc}^* = 450 V
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	ω_0 = $2\pi\times50$ rad/s

II. Single-Phase Grid-Connected PV Inverters

A. System Description

The system configuration and control structure of a single-phase grid-connected PV system are shown in Fig. 2 and its parameters are given in Table I. Here, a dc-dc converter is employed to step up the PV array voltage v_{pv} to match the minimum required dc-link voltage and also provide the control of PV power extraction [32]. This is normally achieved through the regulation of the PV voltage, whose reference (v_{pv}^*) is determined by a Maximum Power Point Tracking (MPPT) algorithm. The PLC strategy can also be implemented in the control of the dc-dc converter, instead of the MPPT algorithm, to limit the PV power extraction to a certain level (below the maximum available power) [33], [34]. The extracted power is then delivered to a full-bridge dc-ac inverter (PV inverter), which provides the grid-integration control including the current control and the grid synchronization [35].

Regarding the power components, IGBT devices from [36] are used. The cooling system (e.g., heat sink sizing) is de-

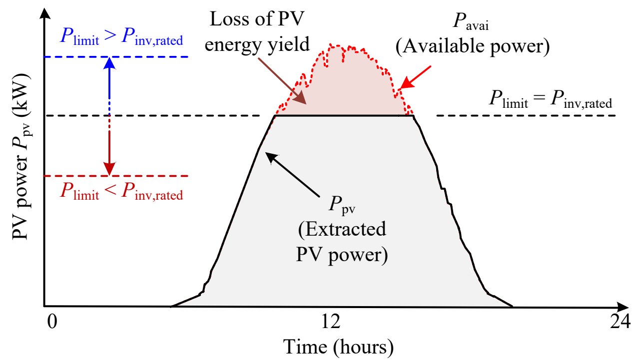


Fig. 3. PV power extraction with the Power-Limiting Control (PLC) strategy (P_{avai}: available PV power, P_{pv}: extracted PV power, P_{limit}: power-limit level, $P_{\text{inv,rated}}$: PV inverter rated power).

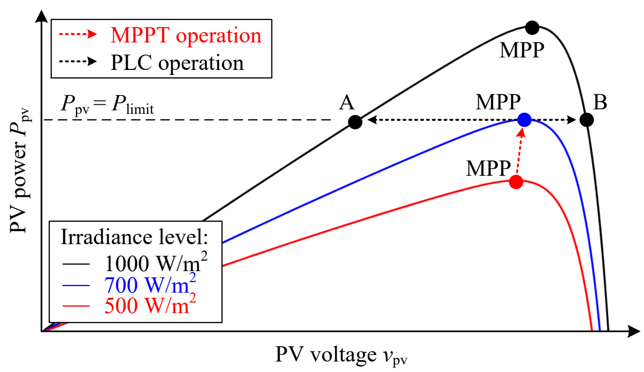


Fig. 4. Operational principle of the PV system with the Power-Limiting Control (PLC) strategy, e.g., the operating point of the PV array is regulated at A or B in order to limit the extracted PV power at $P_{\text{pv}} = P_{\text{limit}}$.

signed to ensure that the power device maximum junction temperature is 100 °C at 120% of the rated power (i.e., 7.2 kW). This ensures a sufficient robustness margin in terms of thermal design. The required dc-link capacitance of the inverter is 1100 μF following the recommendation in [37]. This is realized by connecting two capacitors (2200 μF/350 V) from [38] in series in order to fulfill the voltage requirement.

B. Power-Limiting Control (PLC) Strategy

Instead of always tracking the Maximum Power Point (MPP), the PV output power P_{pv} can be limited to a certain level P_{limit} below the available PV power P_{avai}, as demonstrated in Fig. 3. This operation is called the PLC in the literature, where the PV output power can be summarized as

$$P_{\text{pv}} = \begin{cases} P_{\text{avai}}, & \text{when} \quad P_{\text{avai}} \le P_{\text{limit}} \\ P_{\text{limit}}, & \text{when} \quad P_{\text{avai}} > P_{\text{limit}} \end{cases} \tag{1}$$

where P_{pv} is the PV output power, P_{avai} is the maximum available power (according to the MPPT operation) and P_{limit} is the power-limit level. In order to realize the PLC operation, the operating voltage of the PV array needs to be regulated below the MPP when the available PV power is higher than the power-limit level (i.e., $P_{\text{avai}} > P_{\text{limit}}$) according to (2), as it is also demonstrated in Fig. 4.

$$v_{\text{pv}}^* = \begin{cases} v_{\text{MPPT}}, & \text{when} \quad P_{\text{pv}} \le P_{\text{limit}} \\ v_{\text{pv}} - v_{\text{step}}, & \text{when} \quad P_{\text{pv}} > P_{\text{limit}} \end{cases} \tag{2}$$

where v_{MPPT} is the reference voltage from the MPPT algorithm (i.e., P&O MPPT) and v_{step} is the perturbation step size.

The PLC operation is normally required when the available PV power becomes higher than the PV inverter rated power $P_{\text{inv,rated}}$ [33]. This situation usually occurs in the PV system with over-sized PV arrays (i.e., the PV array is intentionally designed to have higher rated power than the inverter in order to gain more energy under the low solar irradiance condition) [39]. Another incident is due to the solar irradiance reflection from the cloud, resulting in the solar irradiance level higher than 1000 W/m^2. Conventionally, the power-limit level is selected as the inverter rated power (i.e., $P_{\text{limit}} = P_{\text{inv,rated}}$) to ensure the safety of the inverter [39]. However, it should be pointed out that the PLC strategy is capable of flexibly regulating the extracted PV power at any power level below the available power P_{avai} (i.e., $0 \le P_{\text{pv}} < P_{\text{avai}}$), as it is illustrated in Fig. 3. This flexible power controllability is suitable to be employed in the mission profile-oriented control strategy, which will be analyzed in this paper. In fact, the PV inverter rarely operates at its rated power. Thus, the amount of lost energy due to the PLC operation is in general relatively small, while the peak-power and thus loading of the PV inverter can be reduced significantly, which benefits both the PV inverter reliability and the grid congestion. For more details regarding the design and implementation of the PLC strategy, the readers are suggested to follow the reference [33].

III. Reliability Assessment of PV Inverters

In order to assess the reliability of PV inverters, several modeling steps are required, as it is illustrated in Fig. 5. In general, two main reliability evaluation processes are involved:

- Mission profile translation into the thermal stress profile
- Damage calculation of the components

This procedure has been comprehensively explained in [14] and [15], which will be discussed briefly in the following. The mission profiles in Denmark and Arizona will be applied. The lifetime of the components in the PV inverter will be evaluated, where the lifetime of power devices and capacitors are considered as a reliability target.

A. Mission Profile translation into Thermal Stress Profile

The mission profile is important in the reliability assessment and lifetime prediction of PV inverters. Thus, it is usually considered during the reliability evaluation process as it is illustrated in Fig. 5. From the mission profile (i.e., the solar irradiance and ambient temperature), the PV inverter loading (e.g., power losses of the components) is determined from the PV panel model and the control strategy together with the loss model of the components. Then, the power losses are applied to the thermal models of the components (e.g., power devices and capacitors) to obtain the thermal loading during the operation, which is required for the lifetime model.

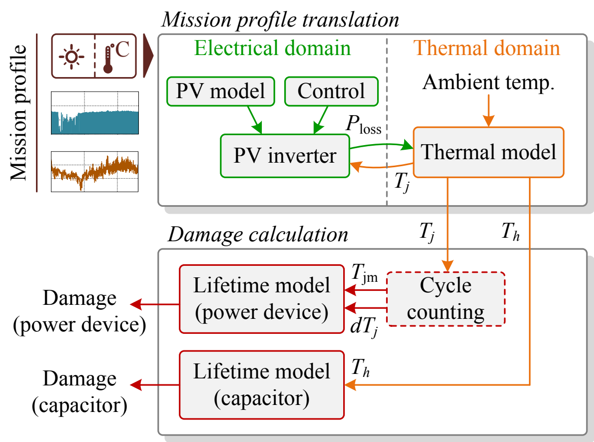
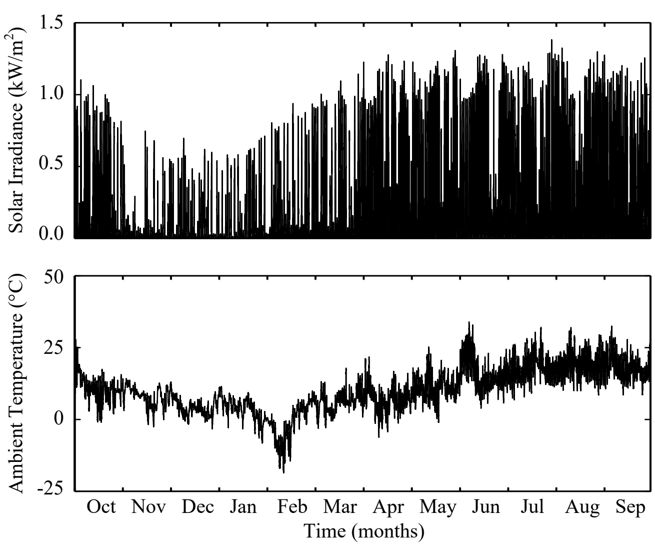
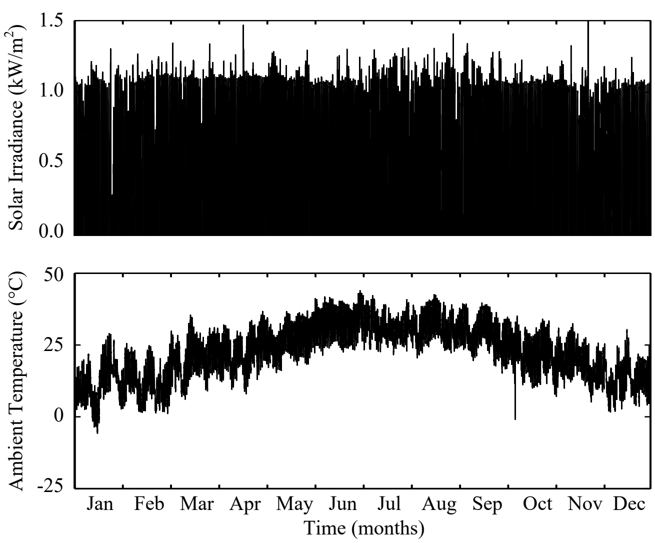


Fig. 5. Reliability assessment of PV inverters based on mission profiles [14].

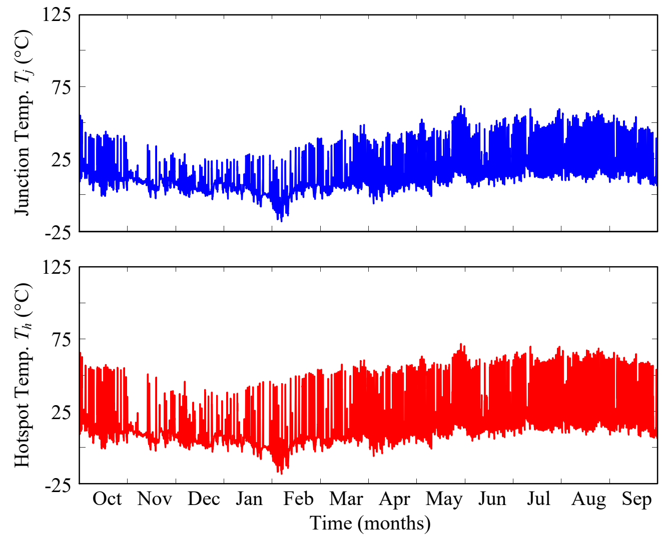


(a)

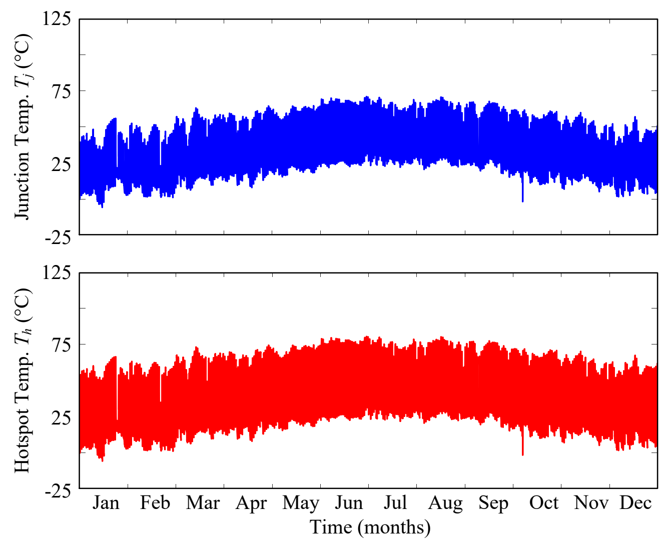


(b)

Fig. 6. Yearly mission profiles (i.e., irradiance and ambient temperature with a sampling rate of 5 mins per sample) in: (a) Denmark and (b) Arizona.



(a)



(b)

Fig. 7. Thermal stress in the power device and capacitor of the PV inverter under one-year mission profile in: (a) Denmark and (b) Arizona.

The mission profiles recorded in Denmark and Arizona are used in this study, as shown in Fig. 6. It can be seen from the mission profiles that the average solar irradiance level in Arizona is constantly high through the year, while the average solar irradiance level in Denmark is relatively low through November to February. The same trend can also be seen in the ambient temperature profile. The mission profiles in Denmark and Arizona represent the installation site in a cold and hot climate condition, respectively. It can be expected from the mission profile that the PV power production of the PV system in Arizona will be higher than that in Denmark.

When translating the mission profile into the inverter loading (following Fig. 5), it can be seen from the thermal stress profiles in Fig. 7 that the PV inverter installed in Arizona experiences a higher thermal loading during the operation. In that case, the reliability-critical components in the system (e.g., power devices and capacitors) will be subjected to higher

TABLE II
PARAMETERS OF THE LIFETIME MODEL OF AN IGBT MODULE [42].

Parameter	Value	Experimental condition
A	3.4368×10^{14}	
α	-4.923	64 K $\leq \Delta T_j \leq$ 113 K
β_1	-9.012×10^{-3}	
β_0	1.942	$0.19 \leq ar \leq 0.42$
C	1.434	
γ	-1.208	0.07 s $\leq t_{on} \leq$ 63 s
f_d	1	
E_a	0.06606 eV	32.5 °C $\leq T_j \leq$ 122 °C
k_B	8.6173324×10^{-5} eV/K	

thermal stresses than those in Denmark. Consequently, the reliability and lifetime of the PV inverter under the two installation sites can differ considerably, which will be demonstrated in the following.

B. Damage Calculation

For the power devices and capacitors, the main cause of component wear-out failures is related to the thermal stress. In the case of power devices (e.g., IGBT), the thermal cycling is one of the main stress factors that cause bond-wire lift-off and solder fatigue after a number of thermal cycles [40], [41]. The number of cycle to failure N_f can be expressed as

$$N_f = A \times (\Delta T_j)^{\alpha} \times (ar)^{\beta_1 \Delta T_j + \beta_0} \times \left[\frac{C+(t_{on})^{\gamma}}{C+1}\right] \times \exp\left(\frac{E_a}{k_b \times T_{jm}}\right) \times f_d \tag{3}$$

which is the lifetime model for IGBT devices [42]. In (3), the thermal cycle amplitude ΔT_j, the mean junction temperature T_{jm}, and cycle period t_{on} are the stress levels obtained from the cycle counting algorithm, and the other parameters are given in Table II.

Normally, it is assumed that the contribution of each thermal cycle to the failure of power device is accumulated linearly and independently during operation following the Miner's rule. This can be further represented as the accumulated damage AD:

$$AD = \sum_i \frac{n_i}{N_{fi}} \tag{4}$$

where n_i is the number of cycles at a certain stress level (T_{jm}, ΔT_j, and t_{on}), and N_{fi} is the number of cycles to failure calculated from (3) at that stress condition. When the damage is accumulated to unity (i.e., AD = 1), the power device is considered to reach its end-of-life. It has been validated experimentally in [43] and [44] that the accuracy of this reliability evaluation approach is acceptable in most cases.

The dc-link capacitor is another lifetime-limiting component in the PV inverter, where the hotspot temperature T_h is the main stress factor. The lifetime model of the aluminum electrolytic capacitor is given as

$$L_f = L_m \times \left(4.3 - 3.3\frac{V_{\text{op}}}{V_{\text{rated}}}\right) \times 2^{\left(\frac{T_m - T_h}{10}\right)} \tag{5}$$

in which L_f is the time-to-failure under the thermal stress level of T_h and the voltage stress level of V_{op} [45], and the other parameters are given in Table III [38].

TABLE III
PARAMETERS OF THE LIFETIME MODEL OF A CAPACITOR [38].

Parameter	Symbol	Value
Rated lifetime (at V_{rated} and T_m)	L_m	3000 hours
Rated operating voltage	V_{rated}	350 V
Rated operating temperature	T_m	105°C

TABLE IV
LIFETIME EVALUATION WITH THE MPPT CONTROL STRATEGY (CONVENTIONAL DESIGN).

Installation site	Lifetime of power device	Lifetime of capacitor
Denmark	33 years	66 years
Arizona	9 years	15 years

Then, the Miner's rule can also be applied to calculate the lifetime of the capacitor as

$$AD = \sum_i \frac{l_i}{L_{fi}} \tag{6}$$

where l_i is the operating time for a set of T_h and V_{op} (e.g., the mission profile time resolution) and L_{fi} is the time-to-failure calculated from (5) at that specific stress condition.

C. Case Study (Conventional MPPT Control Strategy)

Following the reliability assessment method in Fig. 5, the damage occurred in the power device and capacitor during the operation can be calculated and used as a reliability metric. For instance, the operation with high AD indicates low reliability and a high failure rate of the component. In this case study, the MPPT operation is applied to demonstrate the mission profile-dependency of the PV inverter reliability. For the installation site in Denmark, the rated power of the installed PV arrays is 8.4 kW, which is 1.4 times higher than the PV inverter rated power. In this case, the PV arrays are over-sized, which is practical for the installation site with relatively low solar irradiance conditions [39]. However, the same inverter design (i.e., 6 kW) is applied for both installation sites.

By applying the mission profiles in Fig. 6, the corresponding damage of the component in the PV inverter installed in Denmark and Arizona can be obtained, as shown in Fig. 8(a) and (b), respectively. For the mission profile in Denmark, it can be seen in Fig. 8(a) that only small damage occurs in the power device and capacitor of the inverter during winter (e.g., November to February) due to low solar irradiance conditions. In fact, most of the damage occurs from April to August. The AD over one year of the power device and capacitor in the PV inverter is $AD = 3.02 \times 10^{-2}$ per year and $AD = 1.51 \times 10^{-2}$ per year, respectively. This corresponds to the component lifetime of 33 years for the power device and 66 years for the capacitor. Accordingly, the reliability target (i.e., the component lifetime of 20 years) is fulfilled with the designed inverter under the mission profile in Denmark.

For the PV inverter installed in Arizona, the damage in the power device and capacitor is relatively high through the entire year, as it is shown in Fig. 8(b), which reflects the mission profile characteristics. In that case, a one-year

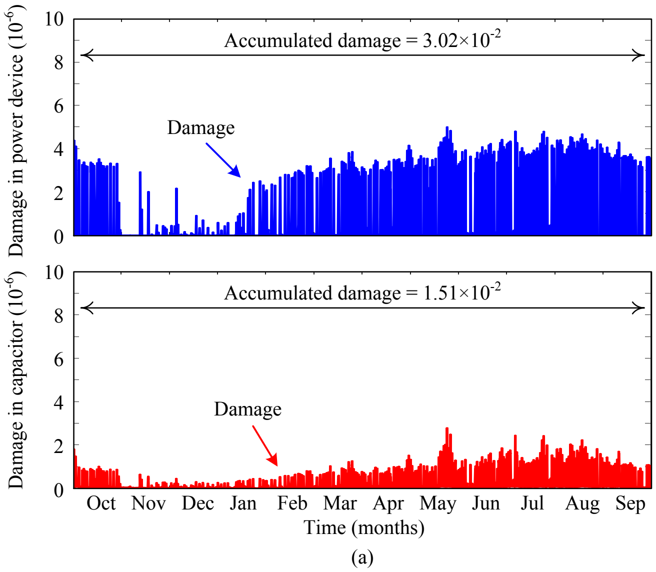


Fig. 8. Damage in the power device and capacitor of the PV inverter under one-year mission profile in: (a) Denmark and (b) Arizona.

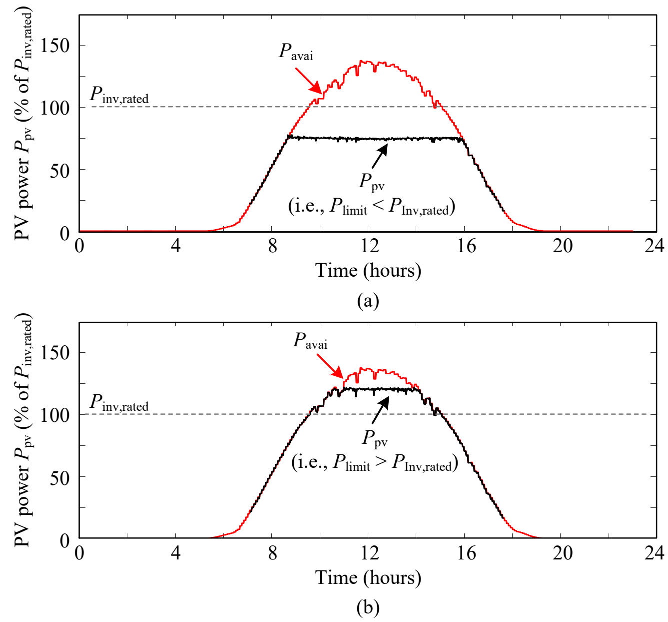


Fig. 9. Power extraction (experimental tests) from a PV inverter with the PLC strategy: (a) $P_{\text{limit}} < P_{\text{inv,rated}}$ and (b) $P_{\text{limit}} > P_{\text{inv,rated}}$ ($P_{\text{inv,rated}}$: PV inverter rated power, P_{avai}: available PV power, P_{limit}: power-limit level).

operation under the Arizona mission profile contributes to the damage of $AD = 11.1 \times 10^{-2}$ per year for the power device and $AD = 6.44 \times 10^{-2}$ per year for the capacitor. Thus, the power device is expected to fail after 9 years, while it is 15 years for the capacitor, as summarized in Table IV. In this case, the reliability target (i.e., the component lifetime of 20 years) is not fulfilled for the given inverter design.

IV. Mission Profile-Oriented Control Strategy

As shown previously, the designed PV inverter in Arizona cannot fulfill the reliability target, while it is considered to be over-designed when installed in Denmark. In the following, the PLC strategy is applied to reshape the inverter reliability according to the mission profile.

A. Control for Reliability

As discussed in Section II, the PLC strategy can be employed to flexibly regulate the extracted PV power (i.e., PV inverter loading) during the operation. However, there is always a trade-off between the PV inverter reliability improvement and the PV energy yield, which needs to be considered when applying the PLC strategy. For instance, decreasing the power-limit level of the PLC strategy below the PV inverter rated power (i.e., $P_{\text{limit}} < P_{\text{inv,rated}}$) will reduce the peak-load of the PV inverter during the operation. This operating condition is demonstrated experimentally in Fig. 9(a), where the power-limit level is kept at 75 % of the PV inverter rated power. By decreasing the power-limit level below the PV inverter rated power, the PV inverter reliability can be improved, as the thermal stress of the components will be reduced [23]. However, the energy yield will also be reduced due to the power curtailment, which is the trade-off of this operation.

On the other hand, more PV energy can be gained by allowing the power-limit level to be higher than the PV inverter rated power (i.e., $P_{\text{limit}} > P_{\text{inv,rated}}$). This operation is applicable in the case of over-sized PV systems, where the PV arrays are installed with the rated power higher than that of the PV inverter. An example of the operation with increasing the power-limit level is demonstrated in Fig. 9(b). In this case, the power-limit level is chosen as 120 % of the PV inverter rated power (which is still within the safe operating area of the components). It can be seen from the results in Fig. 9(b) that the PV energy yield during midday, e.g., 10:00-16:00, is increased due to the increased power-limit level. However, the PV inverter loading will also increase, which may decrease the PV inverter reliability.

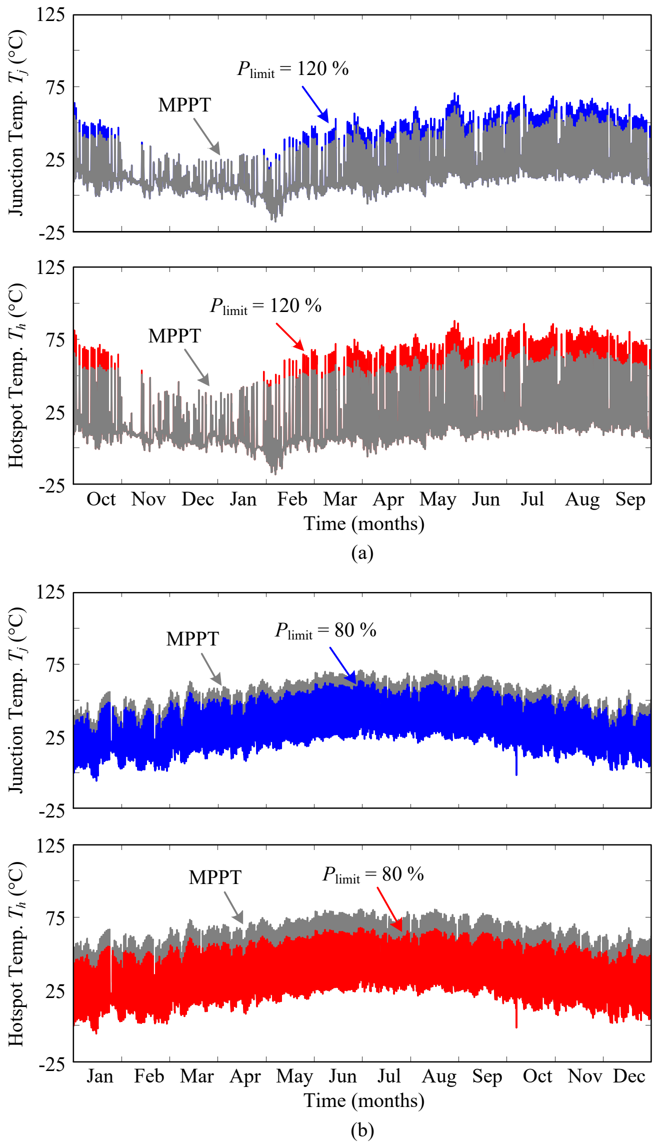


Fig. 10. Thermal stress in the power device and capacitor of the PV inverter operating with the PLC strategy under one-year mission profile in: (a) Denmark (i.e., P_{limit} = 120 %) and (b) Arizona (i.e., P_{limit} = 80 %).

B. Thermal Stress Analysis

In order to demonstrate the impact of the proposed mission profile-oriented control strategy on the long-term operation of the PV inverter, the PLC strategy is applied to the PV inverter considering the two mission profiles in Denmark and Arizona (see Fig. 6). The thermal stress profile of the components in the PV inverter (i.e., power devices and capacitors) during one-year operation is considered and compared with the conventional design solution (i.e., only the MPPT operation).

In Fig. 10(a), the PLC strategy is applied to the mission profile in Denmark with the power-limit being 120 % of the PV inverter rated power (since the PV inverter has been previously considered to be over-designed). It can be seen from the results that the thermal stress level of both the power device and the capacitor is increased compared to the system with only the conventional MPPT operation. However, the increased thermal stress level is still well below the maximum limit of the component (i.e., 150 °C for the power device [36] and 105 °C for the capacitor [38]). On the other hand, the PLC strategy is also applied to the PV inverter installed in Arizona, where the power-limit level of 80 % of the PV inverter rated power is applied in order to improve the reliability. It can be seen from the results in Fig. 10(b) that the thermal stress level of the power device and capacitor is decreased considerably with the PLC strategy compared to the case only with the conventional MPPT operation.

V. Design Guidelines

In this section, design guidelines regarding the selection of power-limit level for a certain mission profile will be provided. The lifetime target of the PV inverter and the PV energy yield are the main design considerations.

A. Lifetime Evaluation

Since the PV inverter installed in Denmark is considered to be an over-designed case compared to the lifetime target of 20 years, the power-limit level should be increased for the mission profile in Denmark. In that case, more energy can be gained with a reduced margin in terms of reliability performance (e.g., lower component lifetime). Notably, the power-limit can be increased up to 120 % of the inverter rated power, following the design in Section II in order to ensure that the components still operate within the safe operating area (according to [36] and [38]). The lifetime of the power device and capacitor of the PV inverter installed in Denmark under different power-limit levels are demonstrated in Fig. 11(a). From the result, it can be seen that the power-limit should not be increased to more than 108.5 % of the inverter rated power, which is the case when the lifetime target of 20 years is marginally fulfilled for the power device.

In contrast, the PV inverter in Arizona should operate with a reduced power-limit level to improve the reliability, since the pre-designed inverter cannot achieve the reliability target. The evaluation results in Fig. 11(b) show that the power device lifetime of 20 years can be achieved, if the power-limit level is kept at 87.5 % of the inverter rated power. By further decreasing the power-limit below 87.5 % of the inverter rated power, the component lifetime can be further increased but it will also result in more energy losses. This is not preferable from the cost-of-energy point of view.

B. PV Energy Yield

As a trade-off of the PLC strategy, the energy yield has to be considered together with the reliability improvement. The relative increase/decrease in the PV energy yield (compared to the case only with the MPPT operation) with different power-limit levels is evaluated and shown in Fig. 12. For the mission profile in Denmark, more PV energy can be extracted by increasing the power-limit level above the inverter rated power. By increasing the power-limit level to 108.5 % of the inverter rated power (i.e., when the obtained lifetime is 20 years), the energy yield is increased by 2.74 %. For the case of the PV

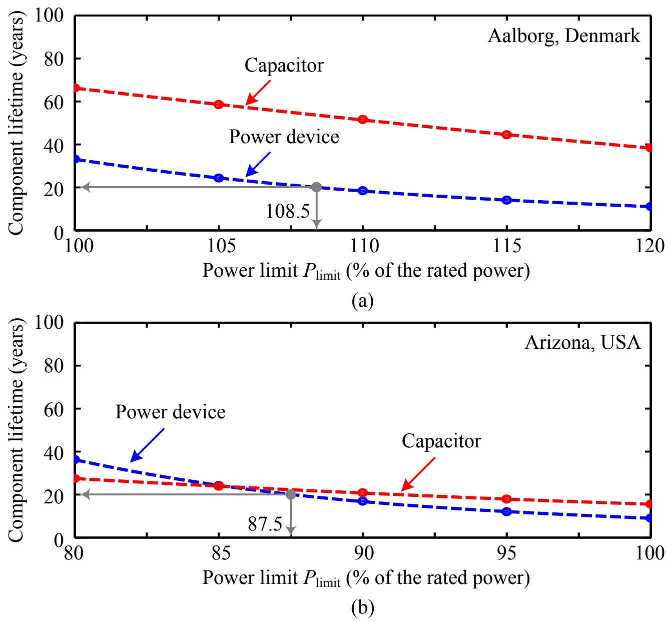


Fig. 11. Lifetime of power device and capacitor with different power-limit levels under one-year mission profile in: (a) Denmark and (b) Arizona.

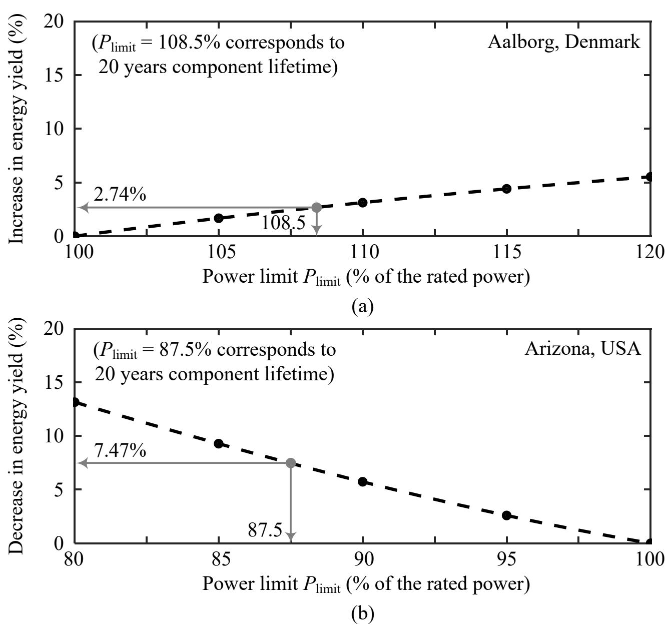


Fig. 12. Impact on the energy yield of the PV inverter with different power-limit levels under one-year mission profile in: (a) Denmark and (b) Arizona.

inverter installed in Arizona, the power-limit level should be decreased to 87.5 % of the inverter rated power considering the inverter lifetime. However, it is worth to mention that setting the power-limit level as 87.5 % of the rated power does not result in 12.5 % of energy losses. This is due to the fact that the PV inverter rarely operates at its rated power. Therefore, only 7.47 % of the energy yield needs to be curtailed to achieve a lifetime target of 20 years. The design results of the power-limit level for different mission profiles are summarized in Table V.

TABLE V
DESIGN RESULTS OF THE MISSION PROFILE-ORIENTED CONTROL STRATEGY.

Mission Profile	Control Strategy	Lifetime	Energy Yield
Denmark	MPPT (P_{limit} = 100 %)	33 years	100 %
	PLC (P_{limit} = 108.5 %)	20 years	102.74 %
Arizona	MPPT (P_{limit} = 100 %)	9 years	100%
	PLC (P_{limit} = 87.5 %)	20 years	92.53 %

The above results suggest that the PLC strategy can offer a degree of freedom to re-shape the reliability performance of the PV inverter for different mission profiles. Thus, it can potentially be employed to minimize the overall cost of solar energy. The trade-off between the reliability and energy yield should be further justified considering the overall cost of energy (including the repair and maintainance cost). For instance, the multi-objective optimization problem to minimize the life-cycle cost of the overall PV system should be used to determine the optimal power-limit level (e.g., depending on the aging level, temperature condition) for each mission profile based on the provided design flow, which is an interesting aspect for the future research.

VI. CONCLUSION

In this paper, a mission profile-oriented control strategy for PV inverters has been presented. The control strategy is based on the power-limiting control scheme, which has been adaptively applied according to the mission profile characteristic. A case study of the mission profiles in Denmark and Arizona has been carried out, where the reliability target is specified as the component lifetime of 20 years. For the Denmark case, where the inverter is over-designed, the energy yield can be increased up to 2.74 % by allowing the PV inverter to operate slightly above the rated power. In contrast, the PV inverter installed in Arizona cannot fulfill the lifetime target only with the conventional MPPT control, when the same inverter design of the Denmark case is adopted. However, by limiting the feed-in power at 87.5 % of the designed inverter rated power, the power device lifetime can be prolonged to 20 years with the compromise of 7.47 % reduction in the energy yield.

REFERENCES

[1] REN21, "Renewables 2019: Global Status Report (GSR)," 2019. [Online]. Available: http://www.ren21.net/.
[2] National Renewable Energy Laboratory, "On the path to sunshot: The role of advancements in solar photovoltaic efficiency, reliability, and costs," Tech. Rep. No. NREL/TP-6A20-65872, 2016.
[3] Fraunhofer ISE, "Current and future cost of photovoltaics. long-term scenarios for market development, system prices and LCOE of utility-scale PV systems," February, 2015. [Online]. Available: http://www.pv-fakten.de/.
[4] M. Taylor, P. Ralon, and A. Ilas, "The power to change: Solar and wind cost reduction potential to 2025," International Renewable Energy Agency (IRENA), Tech. Rep., Jun. 2016.
[5] KIC InnoEnergy, "Future renewable energy costs: solar photovoltaics," Tech. Rep., 2015.
[6] L. M. Moore and H. N. Post, "Five years of operating experience at a large, utility-scale photovoltaic generating plant," *Progress Photovoltaics: Res. Appl.*, vol. 16, no. 3, pp. 249–259, 2008.
[7] A. Golnas, "PV system reliability: An operator's perspective," *IEEE J. of Photovolt.*, vol. 3, no. 1, pp. 416–421, Jan. 2013.

[8] P. Hacke, S. Lokanath, P. Williams, A. Vasan, P. Sochor, G. TamizhMani, H. Shinohara, and S. Kurtz, "A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1097–1112, 2018.

[9] H. A. K. T. J. Formica and M. G. Pecht, "The effect of inverter failures on the return on investment of solar photovoltaic systems," *IEEE Access*, vol. 5, pp. 21 336–21 343, 2017.

[10] R. F. D. J. M. Woodhouse, A. Walker and S. Kurtz, "The role of reliability and durability in photovoltaic system economics," National Renewable Energy Lab.(NREL), Tech. Rep., 2019.

[11] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics: Challenges, design tools, and opportunities," *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 17–26, Jun. 2013.

[12] N. C. Sintamarean, F. Blaabjerg, H. Wang, F. Iannuzzo, and P. de Place Rimmen, "Reliability oriented design tool for the new generation of grid connected pv-inverters," *IEEE Trans. Power Electron.*, vol. 30, no. 5, pp. 2635–2644, May 2015.

[13] K. Ma, H. Wang, and F. Blaabjerg, "New approaches to reliability assessment: Using physics-of-failure for prediction and design in power electronics systems," *IEEE Power Electron. Mag.*, vol. 3, no. 4, pp. 28–41, Dec. 2016.

[14] Y. Yang, A. Sangwongwanich, and F. Blaabjerg, "Design for reliability of power electronics for grid-connected photovoltaic systems," *CPSS Trans. Power Electron. Appl.*, vol. 1, no. 1, pp. 92–103, 2016.

[15] A. Sangwongwanich, Y. Yang, D. Sera, F. Blaabjerg, and D. Zhou, "On the impacts of PV array sizing on the inverter reliability and lifetime," *IEEE Trans. Ind. App.*, vol. 54, no. 4, pp. 3656–3667, Jul. 2018.

[16] H. Huang and P. A. Mawby, "A lifetime estimation technique for voltage source inverters," *IEEE Trans. Power Electron.*, vol. 28, no. 8, pp. 4113–4119, Aug. 2013.

[17] M. Musallam, C. Yin, C. Bailey, and M. Johnson, "Mission profile-based reliability design and real-time life consumption estimation in power electronics," *IEEE Trans. Power Electron.*, vol. 30, no. 5, pp. 2601–2613, May 2015.

[18] P. R. P. E. S. A. T. Bryant, P. A. Mawby and J. L. Hudgins, "Exploration of power device reliability using compact device models and fast electrothermal simulation," *IEEE Trans. Ind. App.*, vol. 44, no. 3, pp. 894–903, May 2008.

[19] S. E. D. Leon-Aldaco, H. Calleja, F. Chan, and H. R. Jimenez-Grajales, "Effect of the mission profile on the reliability of a power converter aimed at photovoltaic applications - a case study," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2998–3007, Jun. 2013.

[20] A. Anurag, Y. Yang, and F. Blaabjerg, "Reliability analysis of single-phase PV inverters with reactive power injection at night considering mission profiles," in *Proc. of ECCE*, pp. 2132–2139, Sep. 2015.

[21] C. Felgemacher, S. Araujo, C. Noeding, P. Zacharias, A. Ehrlich, and M. Schidleja, "Evaluation of cycling stress imposed on IGBT modules in PV central inverters in sunbelt regions," in *Proc. of CIPS*, pp. 1–6, Mar. 2016.

[22] A. Sangwongwanich, Y. Yang, D. Sera, and F. Blaabjerg, "Lifetime evaluation of grid-connected PV inverters considering panel degradation rates and installation sites," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1225–1236, Feb. 2018.

[23] Y. Yang, H. Wang, F. Blaabjerg, and T. Kerekes, "A hybrid power control concept for PV inverters with reduced thermal loading," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6271–6275, Dec. 2014.

[24] M. Andresen, G. Buticchi, and M. Liserre, "Thermal stress analysis and mppt optimization of photovoltaic systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 4889–4898, Aug. 2016.

[25] Y. Yang, E. Koutroulis, A. Sangwongwanich, and F. Blaabjerg, "Pursuing photovoltaic cost-effectiveness: Absolute active power control offers hope in single-phase PV systems," vol. 23, no. 5, pp. 40–49, Sep. 2017.

[26] Energinet.dk, "Technical regulation 3.2.2 for PV power plants with a power output above 11 kW," Tech. Rep., 2016.

[27] F. M. T. Stetz and M. Braun, "Improved low voltage grid-integration of photovoltaic systems in Germany," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 534–542, Apr. 2013.

[28] C. Z. W. L. H. Luo, X. Wang and X. He, "Investigation and emulation of junction temperature for high-power IGBT modules considering grid codes," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 2, pp. 930–940, June 2018.

[29] I. Vernica, K. Ma, and F. Blaabjerg, "Optimal derating strategy of power electronics converter for maximum wind energy production with lifetime information of power devices," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 1, pp. 267–276, Mar. 2018.

[30] D. A. Murdock, J. E. R. Torres, J. J. Connors, and R. D. Lorenz, "Active thermal control of power electronic modules," *IEEE Trans. Ind. App.*, vol. 42, no. 2, pp. 552–558, Mar. 2006.

[31] A. Sangwongwanich, Y. Yang, D. Sera, and F. Blaabjerg, "Mission profile-oriented control for reliability and lifetime of photovoltaic inverters," in *Proc. of IPEC-ECCE Asia)*, pp. 2512–2518, May 2018.

[32] S.B. Kjaer, J.K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1292–1306, Sep. 2005.

[33] A. Sangwongwanich, Y. Yang, F. Blaabjerg, and H. Wang, "Benchmarking of constant power generation strategies for single-phase grid-connected photovoltaic systems," *IEEE Trans. Ind. App.*, vol. 54, no. 1, pp. 447–457, Jan.-Feb. 2018.

[34] A. Sangwongwanich, Y. Yang, and F. Blaabjerg, "High-performance constant power generation in grid-connected PV systems," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 1822–1825, Mar. 2016.

[35] F. Blaabjerg, R. Teodorescu, M. Liserre, and A.V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[36] *SGP30N60*, Infineon Technologies AG, 2007, rev. 2.3.

[37] H. Wang, Y. Yang, and F. Blaabjerg, "Reliability-oriented design and analysis of input capacitors in single-phase transformer-less photovoltaic inverters," in *Proc. of APEC*, pp. 2929–2933, Mar. 2013.

[38] *Type 381LX / 383LX 105 °C High Ripple, Snap-In Aluminum*, Cornell Dubilier, Liberty, SC, USA. [Online]. Available: http://http://www.cde.com/resources/catalogs/381-383.pdf

[39] SolarEdge, "Oversizing of SolarEdge inverters, technical note," Tech. Rep., July 2016.

[40] J. H. F. R. Z. K. S. L. V. Smet, F. Forest and M. Berkani, "Ageing and failure modes of IGBT modules in high-temperature power cycling," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4931–4941, Oct. 2011.

[41] D. D. A. Hanif, Y. Yu and F. Khan, "A comprehensive review toward the state-of-the-art in failure and lifetime predictions of power electronic devices," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4729–4746, May 2019.

[42] U. Scheuermann, R. Schmidt, and P. Newman, "Power cycling testing with different load pulse durations," in *Proc. of PEMD 2014*, pp. 1–6, Apr. 2014.

[43] K. M. U. Choi and F. Blaabjerg, "Validation of lifetime prediction of IGBT modules based on linear damage accumulation by means of superimposed power cycling tests," *IEEE Trans. Ind. Electron.*, vol. 65, no. 4, pp. 3520–3529, Apr. 2018.

[44] T. M. M. S. O. S. G. Zeng, C. Herold and J. Lutz, "Experimental investigation of linear cumulative damage theory with power cycling test," *IEEE Trans. Power Electron.*, vol. 34, no. 5, pp. 4722–4728, May 2019.

[45] *Application guide, Aluminum Electrolytic Capacitors*, Cornell Dubilier, Liberty, SC, USA. [Online]. Available: http://www.cde.com/catalogs/AEappGUIDE.pdf

Ariya Sangwongwanich (S'15-M'19) received the B.Eng. degree in electrical engineering from Chulalongkorn University, Thailand, in 2013, the M.Sc. in energy engineering and the Ph.D. degree from Aalborg University, Denmark, in 2015 and 2018, respectively. Currently, he is working as a Postdoc Fellow at the Department of Energy Technology, Aalborg University.

He was a Visiting Researcher with RWTH Aachen, Aachen, Germany from September to December 2017. His research interests include control of grid-connected converter, photovoltaic systems, reliability in power electronics and high-power multilevel converters. He has co-authored the book – Advanced in Grid-Connected Photovoltaic Power Conversion Systems. In 2019, he received the Spar Nord Foundation Research Award for his Ph.D. thesis.

Yongheng Yang (S'12-M'15-SM'17) received the B.Eng. degree in electrical engineering and automation from Northwestern Polytechnical University, Shaanxi, China, in 2009 and the Ph.D. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 2014.

He was a postgraduate student at Southeast University, China, from 2009 to 2011. In 2013, he spent three months as a Visiting Scholar at Texas A&M University, USA. Dr. Yang is currently an Associate Professor with the Department of Energy Technology, Aalborg University. His current research is on the integration of grid-friendly photovoltaic systems with an emphasis on the power electronics converter design, control, and reliability.

Dr. Yang is the Chair of the IEEE Denmark Section. He serves as an Associate Editor for several prestigious journals, including the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE TRANSACTIONS ON POWER ELECTRONICS. He is a Subject Editor of the IET RENEWABLE POWER GENERATION for Solar Photovoltaic Systems, including MPPT. Dr. Yang is the General Co-chair of the IEEE International Future Energy Challenge (IFEC 2020) and a Publicity Co-chair of the IEEE Energy Conversion Congress and Exposition (ECCE 2020). He was the recipient of the 2018 IET RENEWABLE POWER GENERATION Premium Award and was an Outstanding Reviewer for the IEEE TRANSACTIONS ON POWER ELECTRONICS in 2018.

Dezso Sera (S'05-M'08-SM'15) received his B.Sc. and M.Sc. degrees in Electrical Engineering from the Technical University of Cluj, Romania in 2001 and 2002, respectively; MSc in Power Electronics and PhD on PV systems from Aalborg University, Denmark, Department of Energy Technology, where he currently works as Associate Professor.

Since 2009 he has been programme leader of the Photovoltaic Systems Research Programme (www.pv-systems.et.aau.dk) at the same dept. His research interests include modelling, characterisation, diagnostics and maximum power point tracking (MPPT) of PV arrays, as well as power electronics and grid integration for PV systems.

Frede Blaabjerg (S'86-M'88-SM'97-F'03) was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he got the PhD degree in Electrical Engineering at Aalborg University in 1995. He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. From 2017 he became a Villum Investigator. He is honoris causa at University Politehnica Timisoara (UPT), Romania and Tallinn Technical University (TTU) in Estonia.

His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics and adjustable speed drives. He has published more than 600 journal papers in the fields of power electronics and its applications. He is the co-author of four monographs and editor of ten books in power electronics and its applications.

He has received 31 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, the Villum Kann Rasmussen Research Award 2014 and the Global Energy Prize in 2019. He was the Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2006 to 2012. He has been Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011 as well as 2017 to 2018. In 2019-2020 he serves a President of IEEE Power Electronics Society. He is Vice-President of the Danish Academy of Technical Sciences too.

He is nominated in 2014-2018 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world.